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► **To cite this version:**

Thierry Miquel. Airspeed And Height Profiles Setting For Time Based Flight Arrivals. IEEE CGNCC2014, IEEE Chinese Guidance, Navigation and Control Conference, Aug 2014, Yantai, China. IEEE, pp.978-1-4799-4700-3, 2014. <hal-01059074>

HAL Id: hal-01059074

<https://hal-enac.archives-ouvertes.fr/hal-01059074>

Submitted on 29 Aug 2014

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Airspeed And Height Profiles Setting For Time Based Flight Arrivals

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Abstract: This paper addresses a specific aspect of air traffic control services, namely the achievement of an orderly and expeditious flow of air traffic under time constrained continuous descent approach. More specifically, a futuristic 4D trajectory application where the air traffic controller will ask an aircraft to overfly a meter fix at a specific time is addressed. This paper presents a new methodology to compute reference horizontal and vertical airspeed for time constrained descent which satisfy length and endpoint constraints. The proposed approach is based on the shaping of both the controlled true airspeed (TAS) of the aircraft and its vertical speed. Simulation results illustrate the efficiency of the proposed design with respect to the time and speed constraints.

Key Words: Air Traffic Control Services, Continuous Descent Operation, Time based operations, Speed profiles

1 Introduction

Nowadays, environmental impact and efficiency have become the two very important aspects in aviation industry after safety. New operations, such as Continuous Descent Operation (CDO), can significantly reduce the noise impact of landing aircraft by keeping them longer at higher altitudes and by avoiding steps during descent. Such new operations need a collaborative work between airlines and Air Navigation Service Providers (ANSPs) to be defined and operated. CDO is defined as “*an aircraft operating technique aided by appropriate airspace and procedure design and appropriate ATC clearances enabling the execution of a flight profile optimized to the operating capability of the aircraft, with low engine thrust settings and, where possible, a low drag configuration, thereby reducing fuel burn and emissions during descent. The optimum vertical profile takes the form of a continuously descending path, with a minimum of level flight segments only as needed to decelerate and configure the aircraft or to establish on a landing guidance system (e.g. ILS)*” [1].

Since 2008 European stakeholders have initiated a European CDO implementation program. Up to now, Basic CDO is already in operation at UK Heathrow Airport [2]. In Sweden the European project NUP2 has enabled SAS and LFV to operate 4D flight paths, or green approaches, at Stockholm-Arlanda airport with beneficial impacts on environment. Thanks to the collaboration between Air France and DSNA, CDOs are operated routinely at Marseille airport in France [3].

In United States, a program known as Partnership for AIR Transportation Noise and Emission Reduction (PARTNER), also conducted field tests at Louisville International Airport in 2002 and at Los Angeles International Airport in 2007 [4].

NASA and FAA have been involved in extensive efforts to develop advanced concepts, technologies and procedures for the Next Generation Air Transportation System (NextGen) later on. One aim of NextGen is to develop

ground-side automation systems to assist controllers in strategic planning operations. The En Route Descent Advisor (EDA) is one of the Center TRACON Automation System (CTAS) decision support tools under development at the NASA Ames Research Center. EDA generates maneuver advisories for arrival aircraft to meet scheduled arrival times at the arrival meter fix, sometimes 20 – 25 minutes ahead of the aircraft’s scheduled meter fix arrival time [5]. A research [6] has also been done to develop ground-side automation to enable 4D-Trajectory-Based Operations (4DTBO) in terminal airspace. This research developed and illustrated a computational framework for the design of 4D-Trajectories (4DTs) based on fundamental flight mechanics and nonlinear trajectory optimization techniques with sample scenarios. Furthermore, the 4D-trajectory design process is based completely on open-source models.

AIRE Project (Atlantic Interoperability Initiative to Reduce Emissions) is a joint initiative by the European Commission and the FAA to improve energy efficiency and aircraft noise. AURORA project was a project implemented by Airbus, Scandinavian Airlines International (SAS), Swedish ANSP LFV and Stockholm Arlanda Airport. They conducted Continuous Descent Approaches for the first time on SAS transatlantic flights using an Airbus A330.

Another new ATC technique called Point Merge System (PMS) [7] aimed to facilitate the merging of traffic from a number of Area Navigation (RNAV) arrival routes. The technique is based upon aircraft flying a quasi-arc, up to 30NM long, with a radius of more than 20NM from the designated merging point. Each arc has a published height that the aircraft must have reached before establishing on the arc and a predefined speed to fly it. In general the arc nearest to the merging point has the highest height while the other has the lowest height so that the external sequencing leg is free from traffic from the internal sequencing leg during descent of the traffic. On April 7, 2011, Oslo became the world's first airport to implement a PMS in their airspace. Other countries and airports will follow.

This paper addresses a specific aspect of air traffic control services, namely the achievement of an orderly and expeditious flow of air traffic under time constrained

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continuous descent approach. The task of establishing properly spaced landing sequences is quite demanding for air traffic controllers, especially under heavy traffic conditions. Indeed, terminal control area (TMA) air traffic controllers have to merge two or more streams into a single stream by means of radar vectoring and speed instructions. This high level task of sequencing aircraft is not currently communicated to the pilot. In this paper, the task of merging an aircraft over a specified meter fix is addressed through a novel clearance in which air traffic control clears an aircraft to track an ad-hoc computed reference trajectory. This enables the aircraft to merge at a specified meter fix at a given time. This kind of application may be envisioned as an enhancement of the use of the ground based Arrival MANager (AMAN), which is a tactical controller assistance system enabling the computation of rendez-vous time at meter fix to meet the runway capacity and absorb the traffic [8]. The time computed by the AMAN is envisioned to be used by the air traffic controller to request the aircrew to overfly the meter fix at the desired time. In comparison with current operations, the change is that the controller would communicate decisions on traffic flow organization at a higher level to the pilot rather than requiring the controller to calculate and communicate lower-level guidance instructions.

The main benefit expected from this application is to improve flight efficiency by more precise maneuvering resulting from onboard capabilities, and also noise abatement and fuel saving. More precise maneuvers are also expected to increase sector capacity. More specifically, moving from radar vectoring to monitoring pre-computed trajectories would contribute to decrease controller's workload, and therefore to increase sector capacity.

While keeping the controller responsible for making the traffic flow decisions, the envisioned application involves new avionics capabilities for merging operations, including the tracking of height and speed. Thus, air traffic control improvement is achieved through a greater involvement of pilots in cooperation with air traffic controllers. This type of application is clearly in the scope of the 4D trajectory concept promoted by the European programme SESAR [9] and by the US programme NextGen [10].

In this paper a futuristic 4D trajectory application where the air traffic controller will ask an aircraft to overfly a meter fix at a specific time; this time is assumed to be specified by the air traffic controller to settle properly the arrival sequence and could be given for example through an Arrival Manager (AMAN). In addition, this clearance is assumed to be given after the Top Of Descent (TOD) of the aircraft. This paper addresses the issue of computing a reference airspeed and height for time constrained descent.

This paper is organized as follows: first, the operational concept supporting the novel application is presented. Then, the achievement of vertical and horizontal speed reference profiles for time-based operations at a specified meter fix with continuous descent is presented. The free parameter which enables the coupling between speed profile and height profile is then set in order to achieve a

monotonic calibrated airspeed which is anticipated to be required by the aircrew. An illustrative example is presented throughout the paper. Finally conclusions are drawn and future work is presented.

2 Operational concept

This section illustrates the envisioned concept, already presented in [11]. It is considered that the subject aircraft has been transferred from an En Route sector to a terminal sector. Like the visual clearance, the request for the envisioned application can either be initiated from the ground or from the aircrew. It will be assumed that the application is initiated by the aircrew. In the following, this application will be named 4D Green Approach Trajectory (4D-GAT).

The following example describes the operational implementation of the envisioned application. ABC123 is the subject aircraft transferred from the En Route sector to the terminal sector (TMA). The aircrew is now contacting for the first time the TMA Control Center, which will be named for this illustrative example Toulouse approach. The aircrew of the subject aircraft is requesting a 4D Green Approach Trajectory while transmitting the relevant parameters through data link. Those parameters include the requested level-off IAS over the final approach fix (FAF), descent IAS as well as the requested flight path angle during descent:

- Toulouse approach, ABC123, descending FL150. Request 4D Green Approach Trajectory. Parameters transmitted.

On the ground, the TMA air traffic controller launches the ground based function which sets the reference trajectory to be followed by the aircraft. This reference trajectory is computed by taking into account the requested parameters transmitted by the aircraft as well as wind, end point (the FAF for example) and RTA (Requested Time of Arrival) over that point (which is selected by the air traffic controller). After having checked that the proposed reference trajectory is satisfactory from the air traffic control point of view, the TMA air traffic controller uplinks it to the subject aircraft (with the RTA), and assumes the subject aircraft through a clearance to level off at FL 140, that is at the highest flight level authorized in the sector:

- ABC123, Toulouse approach, continue descent FL140. Cleared 4D Green Approach Trajectory FAF runway 32L (or negative for 4D Green Approach Trajectory)

The aircrew checks the uplinked reference trajectory and indicates its acceptance (or not) with the proposed trajectory. A full exchange through data link messages may also be an alternative.

- Descending FL 140. Cleared 4D Green Approach Trajectory FAF runway 32L, RTA 20:00:20, ABC123

Then the aircrew activates the tracking of the reference trajectory while the air traffic controller indicates the next report:

- ABC123, report FAF runway 32L, 3000 ft QNH 1012

- Report FAF runway 32L, 3000 ft QNH 1012, ABC123

The controller monitors on his/her radar (or ADS/B) display that the reference trajectory is correctly flown. When approaching the FAF, the following phraseology is envisioned:

- Toulouse approach, ABC123, approaching FAF runway 32L, 3000 feet QNH
- ABC123, Toulouse approach, cleared final approach runway 32L, contact Blagnac Tower 123,45
- Cleared final approach runway 32L, contacting Blagnac Tower 123,45

The 4D maneuver finishes when the aircraft overflows the final approach fix (FAF). The reference trajectory is permanently displayed on the controller radar (and/or ADS/B) display in order to monitor the subject aircraft and to provide separation between the subject aircraft and the surrounding traffic during the tracking of the reference trajectory. There is no separation provision delegation as the controller continues to provide separation provision to the subject aircraft.

The aircrew may reject the proposition of 4D Green Approach Trajectory for any reason. Either the pilot or the controller may cancel this kind of operation at any time and for any reason such as operational issue or system failure.

The purpose of the following section is to provide a technical framework of the function in charge of setting both the reference airspeed and vertical profile.

3 Airspeed and height profiles setting

The purpose of this section is to propose a framework to compute a reference horizontal airspeed V_p (that is the horizontal component of the true airspeed) such that the aircraft will overfly a specified meter at a specific time and speed. This means that we are looking for a reference airspeed $V_{pr}(t)$ such that at given time T the aircraft has flown a given distance d_f . In addition, we wish that the aircraft has a given airspeed V_f at time T . Assuming a constant wind denoted W , this can be written as the following two boundaries values problem:

$$\text{find } V_{pr}(t) \text{ s.t. } \begin{cases} V_{pr}(0) = V_0 \\ V_{pr}(T) = V_f - W T \\ l(T) \stackrel{\text{def}}{=} \int_0^T V_{pr}(t) dt = d_f \end{cases} \quad (1)$$

In the following, we will replace time t by the dimensionless parameter τ which is defined by the ratio between actual time t and the duration T to overfly the given meter fix:

$$0 \leq \tau \stackrel{\text{def}}{=} \frac{t}{T} \leq 1 \quad (2)$$

Following previous work [12], we will consider the following expression for reference length $l(\tau)$, where parameters a_0, a_1, a_2 and b are free parameters:

$$\begin{aligned} \frac{l(\tau)}{T} &= a_0 \tau + \frac{a_1}{\sqrt{b}} \operatorname{atan}(\sqrt{b} \tau) \dots \\ &+ \frac{a_2}{\sqrt{b}} (\operatorname{atan}(\sqrt{b}(\tau-1)) + \operatorname{atan}(\sqrt{b})) \end{aligned} \quad (3)$$

Time derivation of the preceding equation leads to the expression of the reference airspeed:

$$V_{pr}(\tau) = a_0 + \frac{a_1}{b \tau^2 + 1} + \frac{a_2}{b(\tau-1)^2 + 1} \quad (4)$$

In order to set the initial value of the reference speed at the current speed of the aircraft and in order to satisfy the constraints presented in (1), parameters a_0, a_1, a_2 and b shall satisfy the following relationships:

$$\begin{cases} V_{pr}(0) \stackrel{\text{def}}{=} V_0 \Leftrightarrow a_0 + a_1 + \frac{a_2}{b+1} = V_0 \\ l(1) = d_f \Leftrightarrow a_0 + \frac{\operatorname{atan}(\sqrt{b})}{\sqrt{b}} (a_1 + a_2) = \frac{d_f}{T} \\ V_{pr}(1) = V_f \Leftrightarrow a_0 + \frac{a_1}{b+1} + a_2 = V_f \end{cases} \quad (5)$$

Assuming that parameter b is already set, parameters a_0, a_1 and a_2 can easily be computed from the preceding equations. Indeed, we get:

$$\begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & \frac{1}{b+1} \\ 1 & \frac{\operatorname{atan}(\sqrt{b})}{\sqrt{b}} & \frac{\operatorname{atan}(\sqrt{b})}{\sqrt{b}} \\ 1 & \frac{1}{b+1} & 1 \end{bmatrix}^{-1} \begin{bmatrix} V_0 \\ \frac{d_f}{T} \\ V_f \end{bmatrix} \quad (6)$$

The time derivative of the airspeed is given by:

$$\frac{dV_{pr}}{dt} = -\frac{2b}{T} \left(\frac{\tau a_1}{(b \tau^2 + 1)^2} + \frac{a_2(\tau-1)}{(b(\tau-1)^2 + 1)^2} \right) \quad (7)$$

The height profile of the aircraft will be computed using the approach: in equations (3) and (4) $l(\tau)$ and $V_{pr}(\tau)$ will be respectively replaced by $h_r(\tau) - h_r(0)$ and $V_{pr}(\tau)$, where $V_{pr}(t)$ represents the reference vertical speed of the aircraft and $h_r(\tau)$ the reference height.

4 Illustrative example

The preceding approach is now illustrated through the following example where the reference horizontal airspeed $V_{pr}(\tau)$ and the reference height $h_r(\tau)$ shall satisfy the following constraints:

$$\left\{ \begin{array}{l}
T=270 \text{ sec} \\
h_r(0)=12500 \text{ feet} \\
V_{zr}(0)=0 \text{ feet/min} \\
V_{pr}(0)=300 \text{ knots TAS} \\
\text{(i.e. 250 knots IAS at 12500 feet)} \\
h_r(T)=4000 \text{ feet} \\
V_{zr}(T)=0 \text{ feet/min} \\
V_{pr}(T)=233 \text{ knots TAS} \\
\text{(i.e. 220 knots IAS at 4000 feet)} \\
l(T) \stackrel{\text{def}}{=} \int_0^T V_{pr}(t) dt = 20 \text{ NM}
\end{array} \right. \quad (8)$$

Setting parameters b to 5 for both horizontal airspeed and vertical speed leads to the following reference horizontal airspeed and vertical speed: we can see that the airspeed is rather continuously decreasing whereas the minimum vertical speed is about -3000 feet/min :

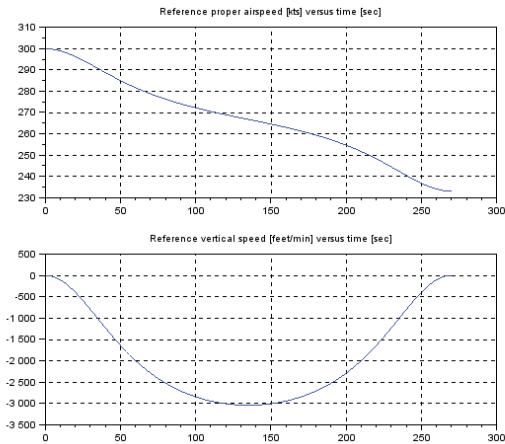


Fig. 1: Reference horizontal airspeed and vertical speed for $b=5$

On the other hand, when setting parameter b to 400 for both horizontal airspeed and vertical speed we get the following reference horizontal airspeed and vertical speed. We can see that the airspeed starts to decrease, then levels off around 265 knots before decreasing again towards the constrained final value of 233 knots, whereas the minimum vertical speed is about -2200 feet/min :

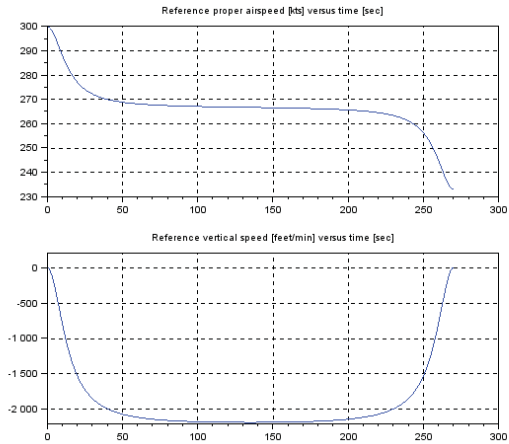


Fig. 2: Reference horizontal airspeed and vertical speed for $b=400$

Thus, the increase of the value of parameter b tends to flatten out the reference speed; as a consequence, the greater parameter b is, the higher the maximal acceleration of the reference speed is; indeed, the area $\int_0^T V_r(t) dt$ (that is the mean airspeed times the duration T) shall remain constant and equal to d_f .

Now that the reference horizontal airspeed and vertical speed are computed, the reference true airspeed (TAS) V_r and flight path angle γ can be computed as follows:

$$\begin{cases} V_{pr} = V_r \cos(\gamma_r) \\ V_{zr} = V_r \sin(\gamma_r) \end{cases} \Leftrightarrow \begin{cases} V_r = \sqrt{V_{pr}^2 + V_{zr}^2} \\ \gamma_r = \text{atan}\left(\frac{V_{zr}}{V_{pr}}\right) \end{cases} \quad (9)$$

At that time, the way to settle the value of parameter b is still under consideration. Nevertheless, some clues are already known such as:

- Parameter b should be chosen such that both reference speed and acceleration are achievable by the aircraft;
- In addition, parameter b should be chosen such that the calibrated airspeed (CAS) of the aircraft increases or decreases monotonically.

As a reminder, the calibrated airspeed (CAS) is measured directly from the dynamic pressure acting on aircraft surfaces and is displayed on the airspeed indicator, which is part of the primary flight display.

Calibrated airspeed (CAS) can be calculated as a function of the true airspeed V as follows [13]:

$$CAS = \left[\frac{2p_0}{\mu \rho_0} \left[\left(1 + \frac{p}{p_0} \left[\left(1 + \frac{\mu \rho}{2p} V^2 \right)^{\frac{1}{\mu}} - 1 \right] \right)^{\mu} - 1 \right] \right]^{\frac{1}{2}} \quad (10)$$

Where:

- ρ is the air density
- ρ_0 is the air density at sea level
- p is the actual pressure
- p_0 is the pressure at sea level
- $\mu = 1/3, 5$

As far as the air density ρ depends on the altitude, it is clear from (10) that the reference calibrated airspeed (CAS) depends on both the reference height h_r and the airspeed V_r .

In the following, the parameter b which is used to compute the reference vertical speed is set to $b_v = 20$. As a consequence the vertical profile is set and we examine the effect of parameter b to compute the true airspeed (TAS) on the resulting calibrated airspeed (CAS), which depends on both the altitude (that is on the fixed parameter b_v) and on true airspeed (TAS).

The following figure shows the resulting calibrated airspeed (CAS) for the previous example when the reference airspeed V_r is obtained with $b = 5$:

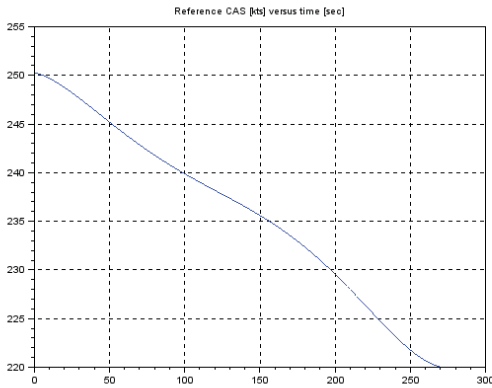


Fig. 3: Calibrated airspeed (CAS) when airspeed is computed with $b = 5$ ($b = 20$ for vertical speed)

It is clear from the preceding figure that the shape of the reference calibrated airspeed is a monotonic function, which will not disturb the aircrew during the maneuver.

The corresponding reference horizontal airspeed ($b = 5$) and vertical speed ($b = 20$) is provided hereafter: it can be seen that the minimum vertical speed is about -3000 feet/min:

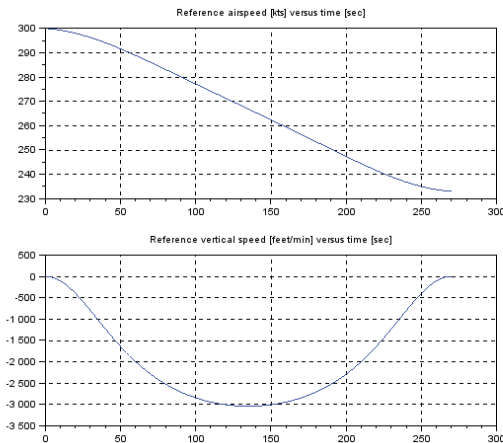


Fig. 4: Reference horizontal airspeed ($b = 5$) and vertical speed ($b = 20$)

Finally, reference along track distance and reference height of the aircraft is shown below. As expected, the

length which is flown is equal to 20 NM, whereas the initial height is 12500 feet and the final height after 270 sec of flight is 4000 feet, which matches the constraints (8).

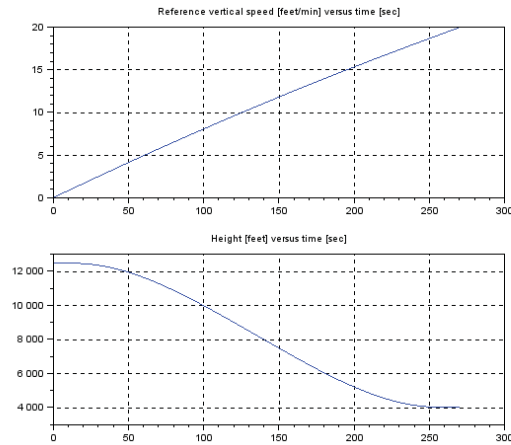


Fig. 5: Reference along track distance ($b = 5$) and reference height ($b = 20$)

On the contrary, setting parameter b to 30 when computing the reference airspeed V_r leads to the following reference calibrated airspeed (CAS):

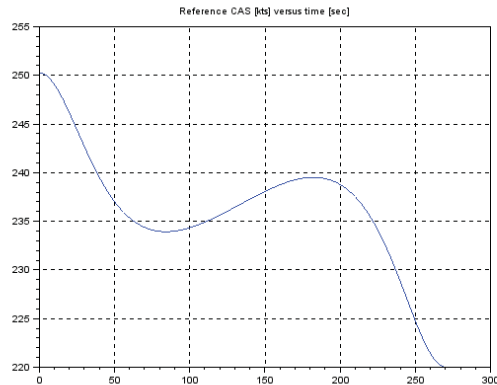


Fig. 6: Calibrated airspeed (CAS) when airspeed is computed with $b = 30$ ($b = 20$ for vertical speed)

It is clear from the preceding figure that the shape of the reference calibrated airspeed is no more a monotonic function: reference CAS starts to decrease, then increase and finally decreases again, which may be incomprehensible to the aircrew and not acceptable from the pilot point of view..

5 Conclusion

This paper addresses a specific aspect of air traffic control services, namely the achievement of an orderly and expeditious flow of air traffic under time constrained continuous descent approach. More specifically, a futuristic 4D trajectory application where the air traffic controller will ask an aircraft to overfly a meter fix at a specific time has been addressed. The overfly time is assumed to be

specified by the air traffic controller to settle properly the arrival sequence and could be given for example through an Arrival Manager (AMAN). In addition, this clearance is assumed to be given after the Top Of Descent (TOD) of the aircraft which implies simple and quick computations.

This paper presents a new methodology to compute reference horizontal and vertical airspeed for time constrained descent which satisfy length and endpoint constraints. The proposed approach is based on the shaping of a parametric reference airspeed, which is applied to the controlled true airspeed (TAS) of the aircraft and its vertical speed.

Simulation results illustrate the efficiency of the proposed design with respect to the time and speed constraints.

Nevertheless the coupling between aircraft altitude and reference true airspeed may result in a non monotonic calibrated airspeed (CAS), which may be a concern for the aircrew. This issue has to be tackled through an appropriate choice of the available degree of freedom in the computation of the reference airspeed (namely parameter b) and will be addressed in future work.

Future developments include the test of the robustness of the proposed design with respect to unexpected wind. This may be addressed through the periodic update of the computation of reference airspeed and vertical speed.

The proposed approach can be extended to the case where constraints over multiple fixes are imposed. Indeed, the way to compute the reference speed takes explicitly into account the initial and final values of aircraft's position and speed and can thus be used to accommodate the reference speed to each segment of flight.

Acknowledgment

The author wishes to thank C. Bertrand for her invaluable support.

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